Physics-based Approach to Density Estimation and Prediction using Orbital Debris Tracking Data

Shaylah Mutschler, Penina Axelrad, Tomoko Matsuo, Eric Sutton

University of Colorado Boulder

THE VISION

Harness the orbital debris population as indirect sensors to estimate parameters of the space environment.

OBJECTIVE

Develop a method that estimates forcing parameters of a physics-based space environment model to allow for improved atmospheric density estimates and Low Earth Orbit (LEO) space object motion predictions.

BACKGROUND

- A key requirement for accurate space object trajectory prediction is knowledge of the non-conservative forces affecting these objects. These effects vary temporally and spatially and are primarily driven by the dynamical behavior of space weather.
- Of all catalogued space objects, 95% are rocket bodies, inactive satellites, or debris, yet their data are still not used for the benefit of updating and adjusting space weather models [1].
- The uncontrolled nature of debris objects can make them particularly sensitive to the variations of space weather.

Fig. 1

- This research focuses on the LEO regime where mismodeling of atmospheric drag is the largest contributor to orbit prediction error.

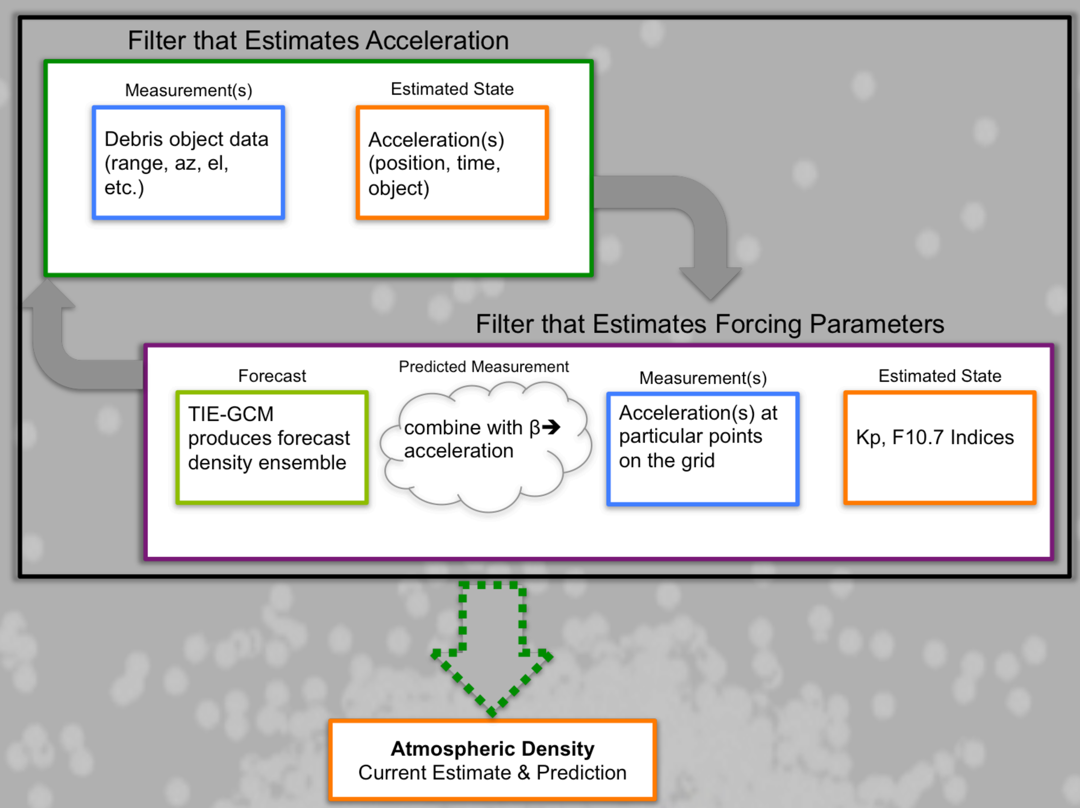
PRIOR WORK

- High Accuracy Satellite Drag Model (HASDM) [2]
  - Observations of carefully selected LEO objects, ~500 observations per day per object
  - Estimates 13 spherical harmonic temperature and density correction coefficients
- Direct Density Correction Method (DDCM) [3]
  - Observations from 16 objects
  - Estimates two correction coefficients to an existing density model
- Emmert, et al. used 5000 TLEs to correct a global density model [4]
- Our work:
  - Aims to take advantage of all debris objects, instead of a small, handpicked portion
  - Estimates forcing parameters of the Thermosphere Ionosphere Electrodynamic General Circulation Model (TIE-GCM)[5]

METHOD

Our tool consists of two filters within a closed-loop feedback system:

1. An Unscented Kalman Filter (UKF) utilizes debris object tracking data in the form of measurements collected from ground sensors to estimate acceleration due to atmospheric drag
2. A Particle Filter or Ensemble Square Root Filter (EnSRF) estimates forcing parameters of TIE-GCM using acceleration due to atmospheric drag (from first filter) as measurements



IMPLEMENTATION

Acceleration due to drag is defined as

$$a_{drag} = -\frac{1}{2}\rho\frac{C_D A}{m}v_{rel}^2\frac{\vec{v}_{rel}}{|\vec{v}_{rel}|}$$

$$\vec{v}_{rel} = \frac{d\vec{r}}{dt} - \vec{\omega}_{\oplus} \times \vec{r}$$

This expression can be expressed in terms of three major components: density (ρ), ballistic coefficient (β), and the relative velocity terms (v_{rel} term)

$$a_{drag} = -\frac{1}{2}\,\rho\,\beta\,v_{rel\ term}$$

UKF (first filter):

- Measurements: debris object range, azimuth, & elevation
- Estimated State: debris object position, velocity, & a_{drag}
- Does not require any information about the density or ballistic coefficient
- The a_{drag} estimates, as well as time, position (altitude, latitude, Local Sidereal Time), and debris object information are passed to the second filter

EnSRF (second filter):

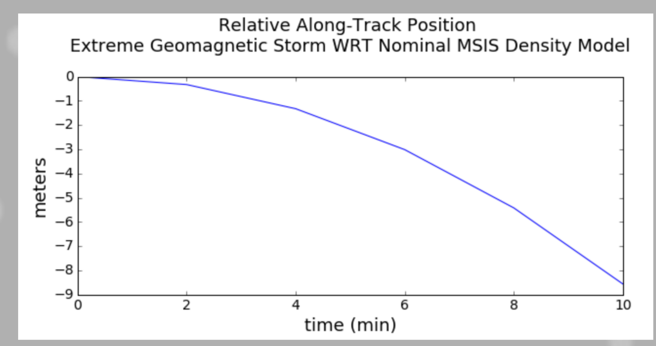
- Measurements: a_{drag}(altitude, latitude, LST, debris object) from first filter
- Estimated State: Kp and F10.7 indices
- TIE-GCM is used to generate an ensemble of forecast density in the filter
  - The density ensemble combined with corresponding debris object ballistic coefficients forms a predicted acceleration measurement.

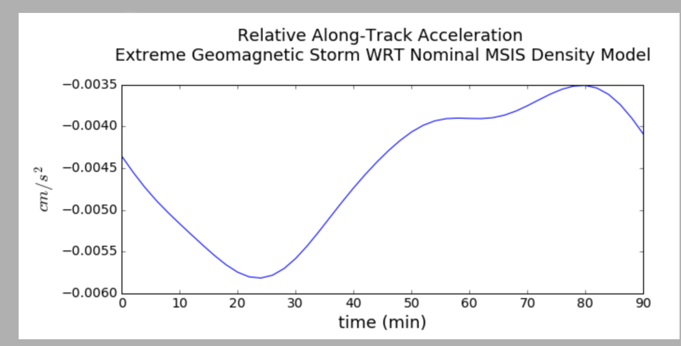
$$a_{drag\ predicted} = -\frac{1}{2}\,\rho_{forecast}\,\beta\,v_{rel\ term}$$

- Corrections are applied to the ensemble of predicted acceleration measurements using the first filter's acceleration estimates as measurements.

OBSERVABILITY

- A LEO object is propagated using two different density conditions (via MSIS[6]):
  1. Nominal/calm conditions (127 F10.7, 17 Ap)
  2. Extreme geomagnetic storm (273 F10.7, 400 Ap)
- The trajectory of the object orbiting through storms conditions is plotted with respect to (WRT) the object orbiting through nominal conditions

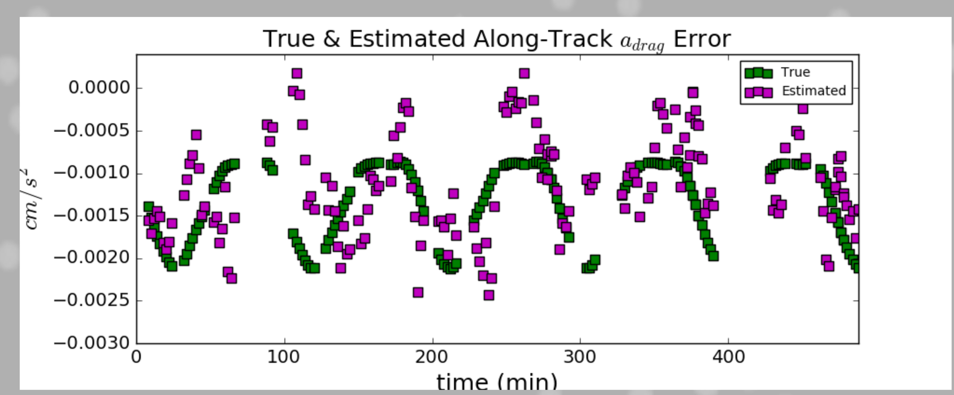


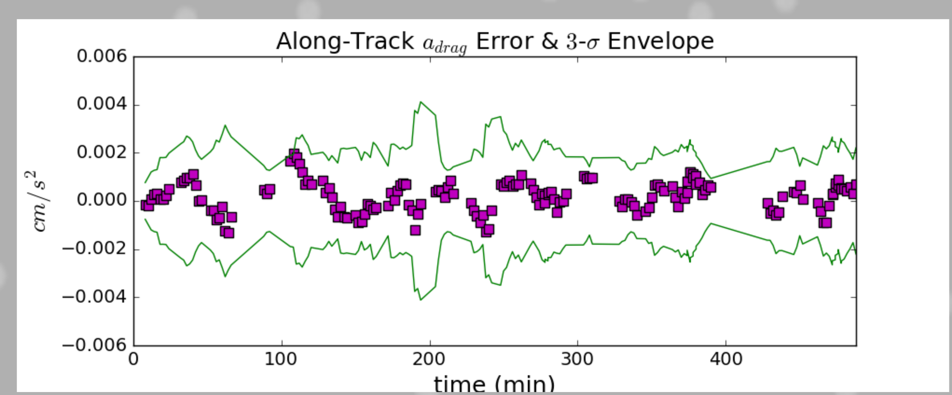


- Difference in relative position after 2 minutes is .32 meters. This difference in relative position continues to grow for the remainder of the simulation.
- Ground sensors measure range (1-σ: .5m), azimuth & elevation (1-σ: 5 arcseconds = 9.7m) from which a_{drag} can be estimated

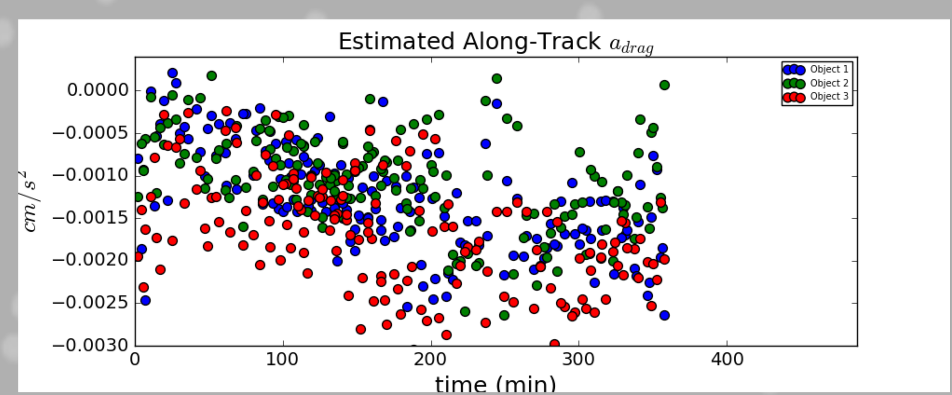
RESULTS

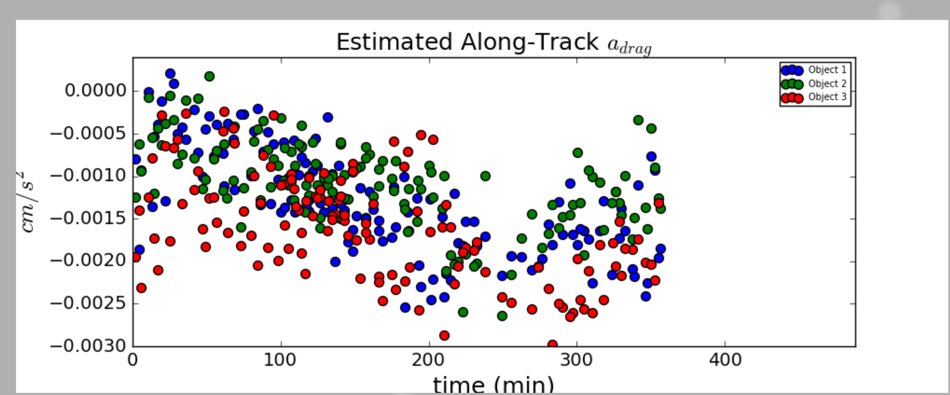
- UKF estimates a_{drag} of simulated LEO object orbiting through nominal density (MSIS generated density field)





- UKF run multiple times for objects with varying β
- Plot below shows all objects' a_{drag} as a function of LST (showing a_{drag} for all times & times after 90 minutes/first orbit (after filter converges)





1. USSTRATCOM Space Control and Space Surveillance. Stratcom.mil. U.S. Strategic Command, 17 Oct. 2016. Web. 5 Sep. 2017.

2. Storz, M.F., Bowman, B.R., Branson, J.I., Casali, S.J., Tobiska, W.K., 2005. High Accuracy Satellite Drag Model (HASDM). Advances in Space Research, 36 (12), 2497-2505.

3. Yurasov, V., Nazarenko, A., Alfriend, K., Cefola, P., 2006. Direct Density Correction Method: Review of Results. In: 57th International Astronautical Congress Conference.

4. Emmert, J., et al.,. 2008. Thermospheric Global Average Density Trends, 1967–2007, Derived from Orbits of 5000 Near-Earth Objects. Geophysical Research Letters, 35. 10.1029/2007GL032809.

5. Roble, R. G., and E. C. Ridley. 1994. A thermosphere-ionosphere- mesosphere-electrodynamics general circulation model (TIME-GCM): Equinox solar cycle minimum simulations (30–500 km). Geophys. Res. Lett., 21 (6), 417–420.

6. Picone, J. M., Hedin, A. E., Drob, D. P., Aikin, A. C. 2002. NRLMSISE-00 Empirical Model of the Atmosphere: Statistical Comparisons and Scientific Issues. Journal of Geophysical Research. 107 (A12), 1468.

Fig.1: thespacereporter.com/2015/05/iss-may-gain-a-laser-cannon-for-blasting-space-debris